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Optimization of double stator PMSM with different slot number in inner and outer stators using genetic algorithm

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Article Info

ABSTRACT

This paper describes the performance enhancement of double stator permanent magnet synchronous machines (DS-PMSM) based on genetic algorithm optimization (GAO). Generally, throughout the development stage, an analytical calculation is implemented to build the initial model of the DS-PMSM since the analytical calculation can provide the initial parameters based on the types and materials used in the machine design. For further improvement, GAO might potentially be applied to provide the optimization technique in searching the optimal motor parameters iteratively and intelligently with specific objective functions. For this aim, a three-phase, DS-PMSM with different number of slots between the outer and inner stators is first designed by using analytical parameter estimation and then later optimized by GAO. The outer and inner stators have 12-slots and 9-slots respectively, while, the rotor carries 10 magnetic poles. Four main input motor parameters, i.e. outer stator slot opening, outer magnet pole arc, inner stator slot opening and inner magnet pole arc are varied and optimized to achieve the design objective functions, i.e. high output torque, low torque ripple, low cogging torque and low total harmonic distortion (THDv). The results from the optimized GAO are compared with the initial motor model and further validated by finite element method (FEM). The results show a good agreement between GAO and FEM. GAO has achieved very significant improvements in enhancing the machine performance.
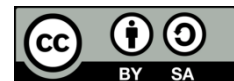
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1. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) are the most reliable and efficient machine that is widely used in home appliances, automations, industrial applications and electric vehicles [1]-[2]. The various emerging applications in PMSM are due to its high efficiency, good dynamic performance, high torque and high-power density [3]-[5]. In the design of PMSMs, generally, the combination of slots to poles is important in determining the types of windings to be used. Fractional slot combinations will indicate non-overlapping windings for the motor, while non-fractional combinations will exhibit overlapping windings. However, the fractional slot motors are more popular due to their inherently low cogging torque, short end-windings and high fundamental winding factor [6]-[8].

The definition of the fractional slot motors is based on the value of the number of stator slots per rotor poles per phase, Nspp. For the fractional slot motor with concentrated windings i.e. Nspp < 1 is usually equipped with coils that span one stator tooth pitch [9]. Additionally, there are numerous PMSM topologies that differ in rotor structures and stator winding arrangements. Surface-mounted PM rotor with fractional concentrated windings is merging as a promising candidate with performance advantages due to good flux-weakening and overload capability [10]. In these machines, the coils belonging to each phase are concentrated and wound on each stator teeth, so that the phase windings do not overlap. This is not only a distinctive manufacturing advantage but is also conducive to higher copper packing factor, higher efficiency and lower possibility of an interphase fault [11]-[12].

Double stator permanent magnet synchronous machines (DS-PMSM) have recently been the subject of extensive research since they have merits such as high torque and high-power density compared to conventional single stator PMSM [13]-[16]. In [13], the double-stator PMSM is applied for Electric Vehicles (EVs) and is also proposed for the dual-channel magnetically integrated charger operations. Double-stator single-rotor has been developed to reduce the cost of manufacturing in machine constructions based on the relative positioning of both stator slots [14]. While other types of DS-PMSM have been investigated to reduce the mechanical stress and weight based on the sizing parameters, while the power density is unchanged [15]. In [16], the DS-PMSM is applied to the wind power generation system where the machine deploys two spatially independent stators for cooling system.

Generally, the slot numbers of the inner and outer stator in DS-PMSM is similar. However, in this paper, the authors propose a DS-PMSM with different numbers of slot-to-pole between inner stator and outer stator. Although the slot numbers of outer and inner stators are different, the ratio of both stators to the rotor is still fractional type. As a result, high winding factor is incorporated into the proposed machine design. To evaluate the performances of DS-PMSM, numerical methods such as the finite element analysis (FEA) have been intensively used for designing and determining the optimal configuration of PMSMs before proceeding to fabrication and manufacture. However, manually varying the important parameters in the machine constructions will require a longer computational time and impractical to achieve the best motor performance [17]-[18].

The duration for designing PMSMs with specific constraints can take a long time when the trial-and-error method is used. Determining the optimal specification related to the multiple objectives required by DS-PMSMs is a challenging task [19]-[21]. To overcome this problem, multi-objective genetic algorithm (MOGA) offer a viable and practical solution to undertake design and optimization problems of DS-PMSMs. With this in mind, a three-phase, DS-PMSM with different number of slots between outer and inner stators is developed in this paper. The combination of slot to pole in outer part is 12-slot/10-pole and in the inner part is 9-slot/10-pole. MOGA is applied to provide the optimization process in searching the optimal motor parameters iteratively and intelligently with specific objective functions. The objective functions are to achieve high output torque, low torque ripple, low cogging torque and low total harmonic distortion (THD).

2.   INITIAL MODEL OF DS-PMSM

The proposed DS-PMSM is a three-phase, permanent magnet (PM) machine of fractional slot type with different slot numbers in the outer and inner stators. The chosen stator and rotor combinations are 12-slot/10-pole for the outer stator/rotor and 9-slot/10-pole for the inner stator/rotor. The initial design of the model is built using FEM. The objectives of the initial design are to characterize its electromagnetic performance such as THD, cogging torque, torque ripple and output torque. This machine performance is further optimized with GAO as discussed in the next section.

Figure 1(a) shows the construction and main parts of the proposed initial design of the three-phase DS-PMSM which consists of 12-slot outer stator, 10-pole rotor and 9-slot inner stator. The rotor carries surface-mounted magnets for both inner and outer surface of the rotor core. Figure 1(b) shows the phase winding layouts in the outer and inner stators of this three-phase DS-PMSM. Double layer windings are applied for both stators. Red color represents the phase A winding, while yellow and blue colors describe the phase B and phase C windings respectively. Detailed dimensions of the proposed DS-PMSM initial model are given in Table 1. Discussion for obtaining the initial dimensions is explained in motor sizing and winding factor under Section 3.
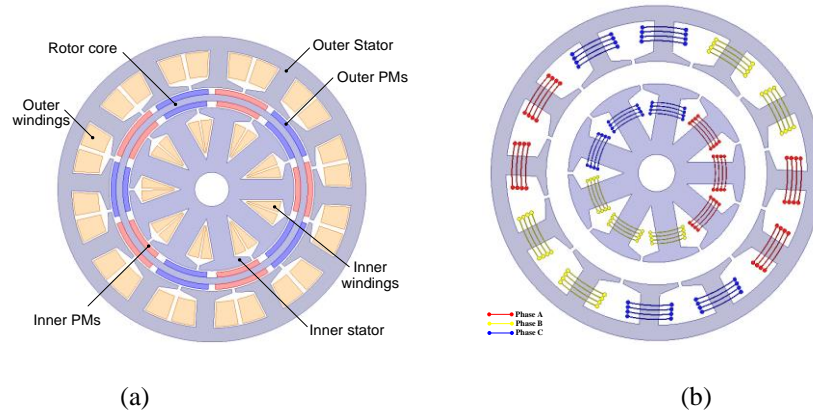
Figure 2. Construction of DS-PMSM, (a) main part, (b) 3-phase non-overlapping windings

Table 1. Parameters and dimensions for the initial model of DS-PMSM

Parameters	Symbols	Values
Outer Stator Slot Number	N_{os}	12
Inner Stator Slot Number	N_{is}	9
Rotor Pole Number	$2p$	10
Outer Stator Outer Radius (mm)	R_{oso}	90
Outer Stator Inner Radius (mm)	R_{osi}	60
Inner Stator Outer Radius (mm)	R_{iso}	48
Inner Stator Inner Radius (mm)	R_{isi}	12
Rotor Outer Radius (mm)	R_{ro}	59
Rotor Inner Radius (mm)	R_{ri}	49
Outer Magnet Outer Radius (mm)	R_{omo}	59
Outer Magnet Inner Radius (mm)	R_{omi}	56
Inner Magnet Outer Radius (mm)	R_{imo}	52
Inner Magnet Inner Radius (mm)	R_{imi}	49
Stack Length (mm)	l_s	40
Outer Air-gap Length (mm)	h_{og}	1
Inner Air-gap Length (mm)	h_{ig}	1
Outer Magnet Thickness (mm)	h_{om}	3
Inner Magnet Thickness (mm)	h_{im}	3
Magnet Remanence (T)	B_r	1.12
Saturation Flux density (T)	B_{max}	1.6
Relative Recoil Permeability	μ_r	1.05
Rated Speed (rpm)	r_m	600
Outer Stator Tooth Body width (mm)	w_{otb}	10.4
Inner Stator Tooth Body width (mm)	w_{itb}	12
Outer Stator Winding Turns per coil	N_{oc}	114
Inner Stator Winding Turns per coil	N_{ic}	50

3. MOTOR SIZING AND WINDING FACTOR

In double-stator PM machine, the total area of the inner stator is inherently smaller than outer stator because the inner stator position is inside the DS-PMSM structure. Therefore, the slot number of the inner stator is preferably selected to be lower than that of the outer stator. This allows more space for the slot area in the inner stator which can accommodate higher number of winding turns. To estimate the initial values of motor dimensions and main geometric parameters, (1) to (6) are applied to determine the inner bore for outer stator part [22].

$$\frac{D_{osi}}{D_{oso}} = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \tag{1}$$

$$a = 2\left[\frac{k\pi}{p}\left(\frac{k\pi}{p} + 2 \right)\left(\frac{B_{og}}{B_{max}} \right)^2 + 2\frac{B_{og}}{B_{max}} - 1 \right] \tag{2}$$

$$b = \frac{3}{2}\left[-2\left(\frac{k\pi}{p} + 1 - 2\frac{w_{tt}}{D_{oso}} \right)\left(\frac{B_{og}}{B_{max}} \right) - 4\frac{w_{tt}}{D_{oso}} \right]$$

(3)

$$c = 1 - 4\left(\frac{w_{tt}}{D_{oso}} \right)^2$$

(4)

$$k = \frac{1}{3}$$

(5)

$$B_{og} = \frac{B_r}{1 - \mu_o \dfrac{h_{og}}{h_{om}}}$$

(6)

Where D_{osi} is the outer stator inner diameter, D_{oso} is the outer stator outer diameter, k is the constant for concentrated winding, B_{og} is the average outer airgap magnetic flux density and B_{max} is the maximum flux density in the stator tooth. The rotor and inner stator dimensions are bound to be based on the inner bore of outer stator size.

The magnitude of the phase back-emf is influenced by the winding factor, K_{dpn}. Because the double-stator motor has two stators, the combination of each stator against the rotor is different, resulting in different K_{dpn} values, namely the winding factor in the inner stator, K_{dpin} and the winding factor in the outer stator, K_{dpon}. The derivations of K_{dpin} and K_{dpon} are given in (7) and (8), where N_s is the number of stator slots, p is the number of rotor pole pairs, and n is the harmonics numbers. The open-circuit flux-linkage per phase, ψ_{phase} of the inner and outer stator motor can be estimated by (9) and (10), where R_{os}, R_{is}, B_{gon}, B_{gin}, l_a, N_p, and ω_r are the outer stator bore radius, inner stator bore radius, magnitude of outer airgap flux density, magnitude of inner airgap flux density, motor active axial length, number of winding turns per phase, and rotor angular speed in rad/s. Subsequently, the phase back-emf for outer and inner stators which is the rate of change of inner and outer phase flux-linkage can be estimated by (11) and (12). The total back-emf for each phase can be given in (13).

$$K_{dpon} = \sin^2 \frac{np\pi}{N_s}$$

(7)

$$K_{dpin} = \frac{1}{3}\sin\left(\frac{np\pi}{N_s} \right)\left[1 - 2\cos\left(\frac{np2\pi}{N_s} \right) \right]$$

(8)

$$\psi_{phase,os} = 2N_p l_a R_{osi} \cdot \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{np} B_{gon} K_{dpon} \cos(np\theta)$$

(9)

$$\psi_{phase,is} = 2N_p l_a R_{iso} \cdot \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{np} B_{gin} K_{dpin} \cos(np\theta)$$

(10)

$$EMF_{phase,os} = 2N_p l_a R_{osi}\omega_r \cdot \sum_{n=1,3,5,\ldots}^{\infty} B_{gon} K_{dpon} \sin(np\omega_r t)$$

(11)

$$EMF_{phase,is} = 2N_p l_a R_{iso}\omega_r \cdot \sum_{n=1,3,5,\ldots}^{\infty} B_{gin} K_{dpin} \sin(np\omega_r t)$$

(12)

$$EMF_{phase} = EMF_{phase,os} + EMF_{phase,is}$$

(13)

4. OPTIMIZATION TECHNIQUE

Genetic algorithm (GA) is one of the artificial intelligent optimization methods. GA begins the optimization process with a set of random chromosomes. Population-based GA is the basis of the survivor of the most powerful individual and transmission of its genetic characteristic to the next generations [23]. The

algorithm operates on three simple genetic operators called selection, crossover and mutation. The selection is carried out using the fitness function, and these operators are applied to obtain better population generation. During the selection, the 'parent' individuals aimed at producing 'child' chromosomes are chosen. The fitness value determines which chromosomes to survive and generate the population of the next generation [24]. Crossover's main objective is to ensure that the genes are shared and that the children inherit the parent's genes. The mutation operator replaces a gene with another gene in the same chromosome. Mutation helps the population to achieve variety and diversity. The selection process, crossover and mutation will continue until some form of convergence criterion has been met or by a fixed number of generations [25]. Flow chart of the genetic algorithm optimization (GAO) is shown in Figure 2 which displays the overall procedures of optimization and evaluation processes.
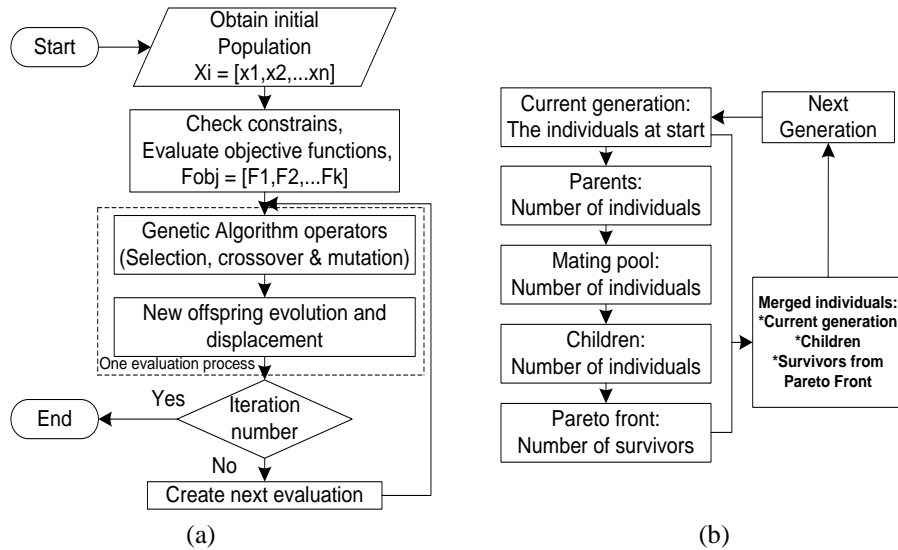

Figure 2. Flow chart of GA optimization, (a) overall process, (b) one evaluation process

5. OBJECTIVE FUNCTIONS

The design optimization of DS-PMSM in this paper is based on the multi-objective functions from GA optimization. Four objective functions are considered, i.e. to have lowest total harmonics distortion of line back-emf, F1; to have lowest cogging torque, F2; to have lowest torque ripple, F3; and to have highest electromagnetic torque, F4. The optimization results will be in vector form for each objective function and can be simplified as indicated in (14). Magnitude with the minimum values of these function will be considered in a group of high performances from the input parameters created by GA process. The Pareto-chart is applied to identify the best motor parameters that give the best motor performances.

$$\mathcal{F}_{obj} = [\ \mathcal{F}_1,\ \mathcal{F}_2,\ \mathcal{F}_3,\ \mathcal{F}_4']_{min} \tag{14}$$

6. OPTIMIZED PARAMETERS

Figure 3 illustrates the DS-PMSM motor parameters. There are two types of geometric parameters in DS-PMSM described as either fixed or variable parameters. The fixed parameters are labelled in black colour, while the variable parameters are labelled in red colour. The variable parameters will become the input parameters which can be varied based on the GAO selection in order to achieve the multi-objective functions. Due to the importance of magnetic flux density in both air-gaps, then four parameters near the outer and inner air gap regions will be optimized, i.e. inner magnet pole arc, α_i; inner slot opening, b_i; outer magnet pole arc, α_o; and outer slot opening, b_o. These variable input parameters have lower and upper boundaries as given in Table 2.

Figure 3. DS-PMSM motor with main parameters

Table 2. Boundaries of four input parameters for GAO

Parameters	α_i (°)	b_i (mm)	α_o (°)	b_o (mm)
Minimum	24	1.5	24	1.5
Maximum	36	3	36	3

7. RESULTS AND DISCUSSION

DS-PMSM motor is initially applied with 50 turns per coil for the inner stator and 114 turns per coil for the outer stator. A sinusoidal phase current of 6 A peak current is excited into both inner and outer stator windings. The initial motor model generates 2.82% THDv, 0.247Nm cogging torque, 4.94% torque ripple and 21.50Nm output torque. The proposed DS-PMSM motor is then optimized by GAO, and the multi-objective functions are set as Fobj expressed in (14). Four input variables for the GAO process are chosen as listed in Table 2. After 30 generations of GA, the optimized process has approached to the optimal solution. Each solution candidate of the population is decoded into a set of machine parameters.

To distinguish the best motor parameters, two pareto charts are created to tabulate the four objective functions as shown in Figure 4 and Figure 5. In the figure legends, "GA" means the genetic algorithm optimization. "Initial" means the output from the initial motor parameters as given in Table 1. The optimization process should fulfill the four objective functions, i.e. lowest line back-emf THDv, lowest cogging torque, lowest torque ripple and highest output torque. As can be seen, a group of the best motor performance is identified in the square dotted line. From this group, the best selected point is chosen with the output performance of 2.17% THDv, 0.178Nm cogging torque, 4.29% torque ripple and 21.32Nm output torque as shown by a red color in both Figure 4 and Figure 5. The selected point has their own optimized machine parameters where the inner slot opening b_i, inner magnet arc α_i, outer slot opening b_o and outer magnet arc α_o as listed in Table 3.

Figure 4. THDv-torque ripple vs cogging torque

Figure 5. THDv-torque ripple vs output torque

Table 3 shows the input parameters for the DS-PMSM motor with output performance for initial model and the optimized model from GAO. Referring to tab GA-Initial (%), after GA optimization, the machine achieves 23.0% reduction in total harmonic distortion of line back-emf THDv, 27.9% reduction in cogging torque, 13.2% reduction in torque ripple and almost the same output torque. Clearly, the optimized

DS-PMSM machine has an improved performance after being subjected with GAO process. The optimized machine shows results with lower THDv, low cogging torque, low torque ripple but similar output torque.

Table 3. Initial and optimized parameters with output performance of DS-PMSM

Parameters	Initial	GA	GA - Initial (%)
Inner magnet arc, α_i [°]	36	33.8	-6.1
Inner slot opening, b_i [mm]	2	2.9	45.0
Outer magnet arc, α_o [°]	36	33.3	-7.5
Outer slot opening, b_o [mm]	2	1.5	-25
Magnet height, h_m [mm]	3	3	0
Airgap thickness, b_g [mm]	1	1	0
Outer stator radius, R_{so} [mm]	90	90	0
Coil slot area, A_c [mm^2]	171.3	171.3	0
Harmonic distortion, $THDv$ [%]	2.82	2.17	-23.0
Cogging torque, T_{cog} [Nm]	0.247	0.178	-27.9
Torque ripple, T_{ripple} [%]	4.94	4.29	-13.2
Average output torque, T_{avg} [Nm]	21.5	21.3	-0.9

8.   FURTHER VALIDATION OF OPTIMIZED MACHINE MODEL

To compare the motor performance and its accuracy from GAO in designing DS-PMSM, the optimal machine parameters are built to confirm its performance in FEM. Figure 6 (a) and Figure 6 (b) illustrate the magnetic flux density distribution under no-load condition before and after optimized respectively. Before optimization, the peak flux density in stator teeth is about 1.56T, and after being optimized, the flux density is slightly reduced to 1.54T due to smaller magnet pole arc at inner and outer magnets.

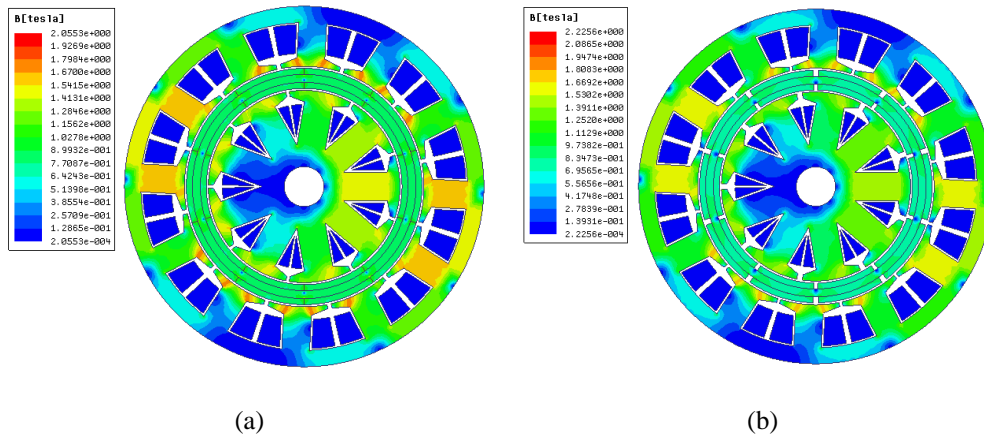(a)   (b)

Figure 6. Magnetic flux density distribution, (a) initial model, (b) best model from GA

The line back-emf, cogging torque and electromagnetic torque waveforms from the initial model and optimized model of DS-PMSM are compared and evaluated. After GAO, the shape of the back-emf waveform is more sinusoidal compared to the initial model due to the decrement of the THDv percentage as shown in Figure 7 (a) for phase back-emf and Figure 7 (b) for line back-emf. Figure 8 (a) shows the cogging torque waveforms which clearly indicates a significant reduction of cogging torque after GAO. The optimized DS-PMSM from GAO also produces smaller torque ripple which can contribute to lesser machine vibration and noise. The average output torque is not much affected before and after the optimization which is a good merit. The optimized motor also achieves reduction in torque ripples as shown in Figure 8 (b).
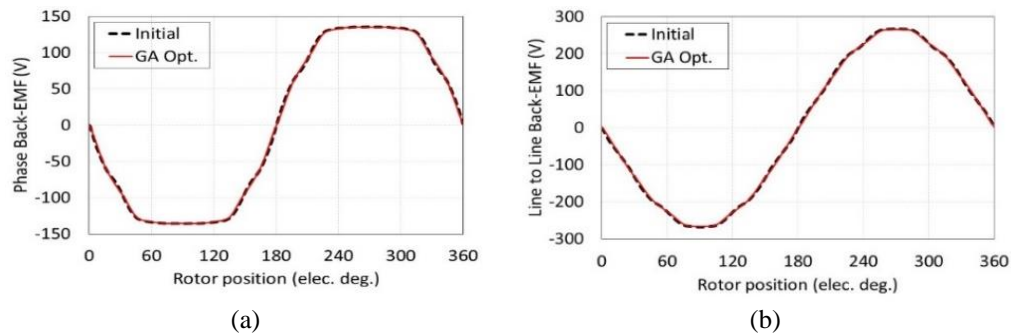
(a)   (b)

Figure 7. Back-emf waveforms, (a) phase back-emf, (b) line back-emf

(a)   (b)
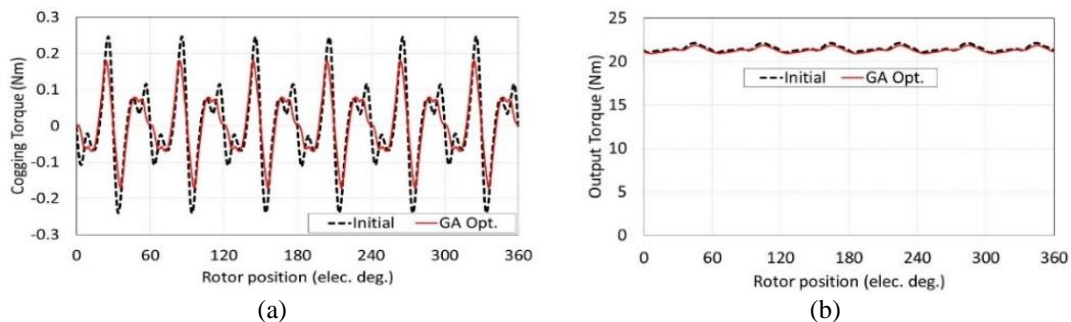
Figure 8. Motor performance, (a) cogging torque waveform, (b) output torque waveform

9.   CONCLUSION

This paper has described the optimization technique on the performance of a three-phase, DS-PMSM machine in which the slot numbers of inner stator and outer stator are different. The improvement of the machine performance using genetic algorithm optimization has been intensively investigated and compared using 2D FEM. Four motor parameters are optimized i.e. inner slot opening, inner magnet arc, outer slot opening and outer magnet arc. The multi-objective functions are to have lower THDv, lower cogging torque, lower torque ripple and higher output torque. The pareto chart is used to tabulate the potential motor performance for certain optimized motor parameters. Pareto chart also provides the freedom to choose the suitable motor performance based on multi-objectives set earlier. The optimized DS-PMSM having 12 slots for the outer stator, 10 poles for the rotor and 9 slots for the inner stator motor has managed to reduce THDv, cogging torque and torque ripple, while maintaining the average output torque. The results from FEM have also confirmed the accuracy of the motor performance from GAO in designing the DS-PMSM machines.

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